



(12) UK Patent (19) GB (11) 2 392 932 (13) B

(45) Date of publication: 23.06.2004

(54) Title of the invention: A Paraboloid expansion cone

(51) Int Cl⁷: E21B 43/10, F16L 13/14

(21) Application No: 0320579.6

(22) Date of Filing: 07.07.2000

Date Lodged: 02.09.2003

(30) Priority Data:

(31) 60143039 (32) 09.07.1999 (33) US

(31) 60146203 (32) 29.07.1999 (33) US

(62) Divided from Application No
0200161.8 under Section 15(4) of the Patents
Act 1977

(43) Date A Publication: 17.03.2004

(52) UK CL (Edition W):
E1F FLA

(56) Documents Cited:
None

(58) Field of Search:
As for published application 2392932 A viz:
UK CL (Edition V) E1F
INT CL⁷ E21B, F16L
Other: ONLINE: WPI,EPODOC,JAPIO
updated as appropriate

(72) Inventor(s):

Robert Lance Cook

David Paul Brisco

R Bruce Stewart

Reece Edward Wyant

Lev Ring

James Jang Woo Nahm

Richard Carl Haut

Robert Donald Mack

Alan B Duell

Andrei Filippov

(73) Proprietor(s):

Shell Internationale Research

Maatschappij B.V.

(Incorporated in the Netherlands)

Carel van Bylandtlaan 30, NL-2596 HR,

The Hague, Netherlands

(74) Agent and/or Address for Service:

Haseltine Lake & Co

Imperial House, 15-19 Kingsway,

LONDON, WC2B 6UD, United Kingdom

2392432

1/15

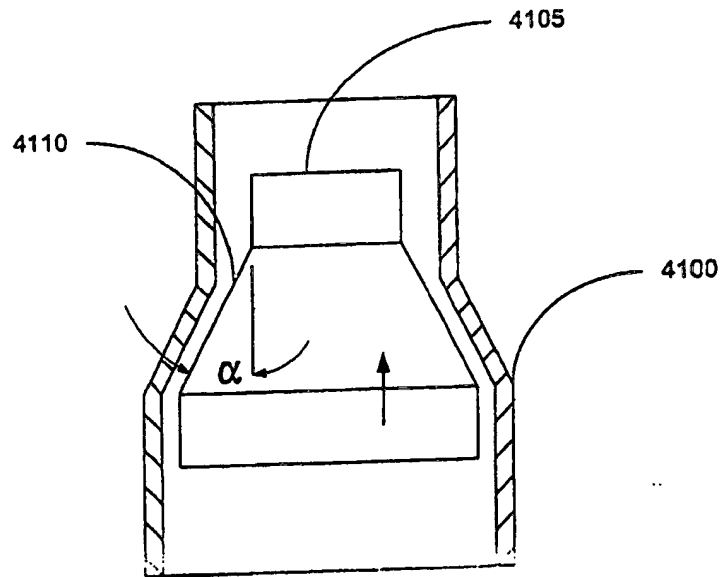


FIGURE 1

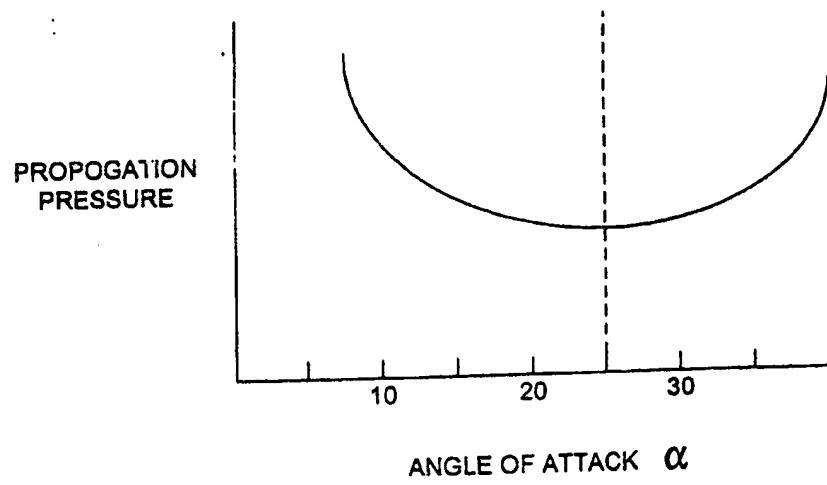


FIGURE 2

2/15

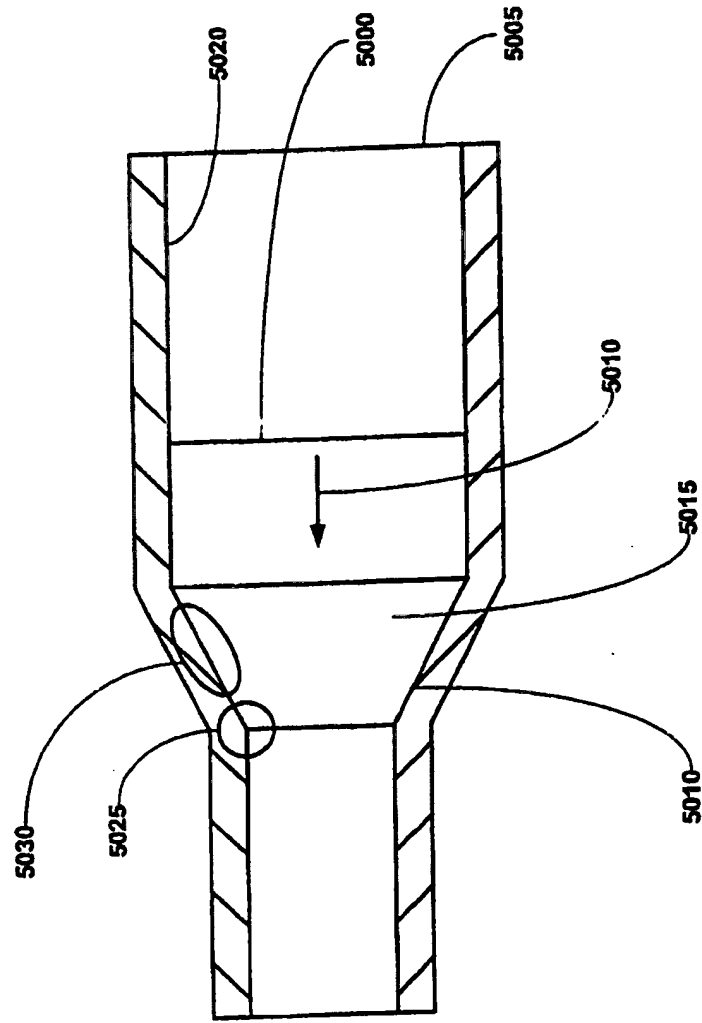
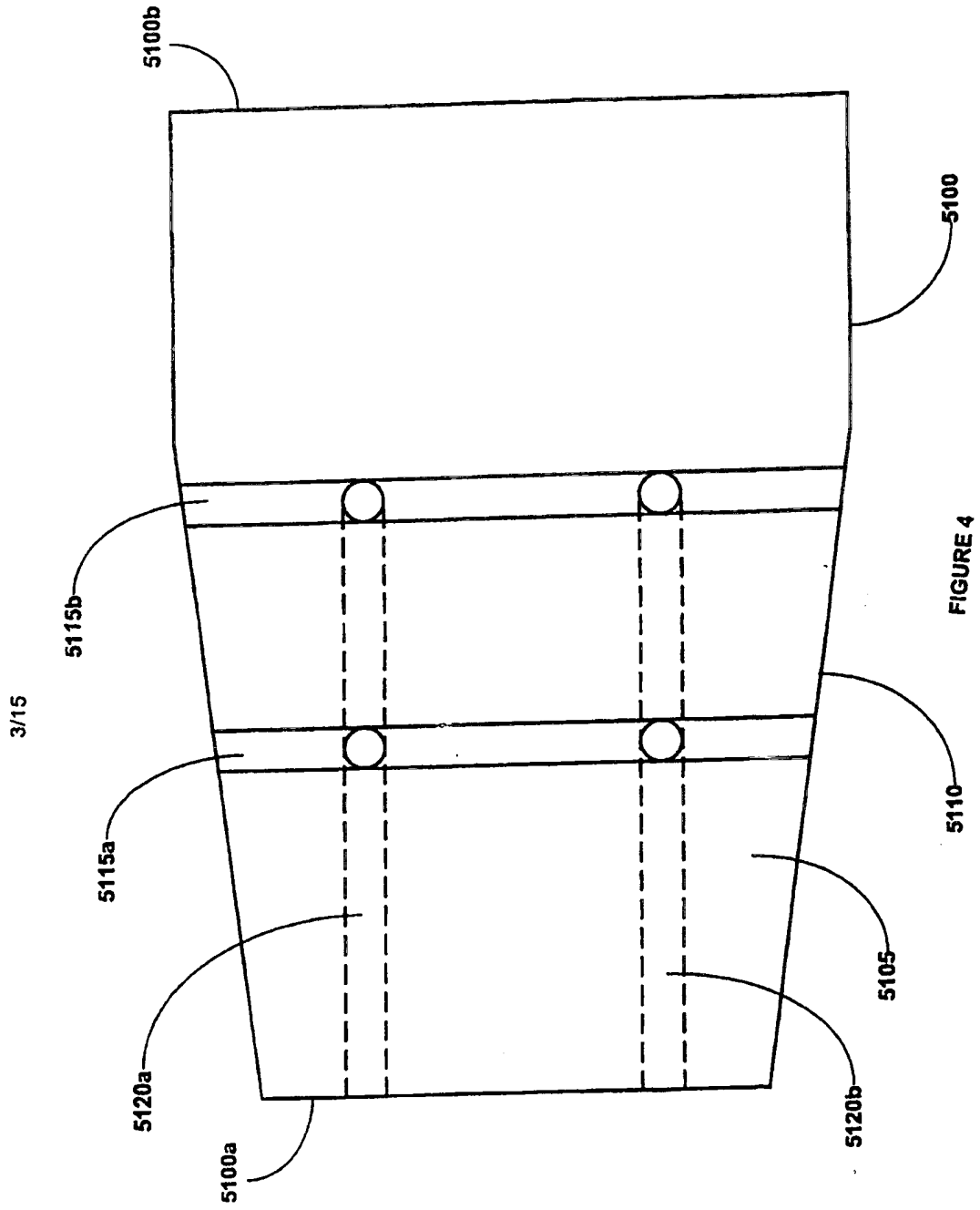


FIGURE 3



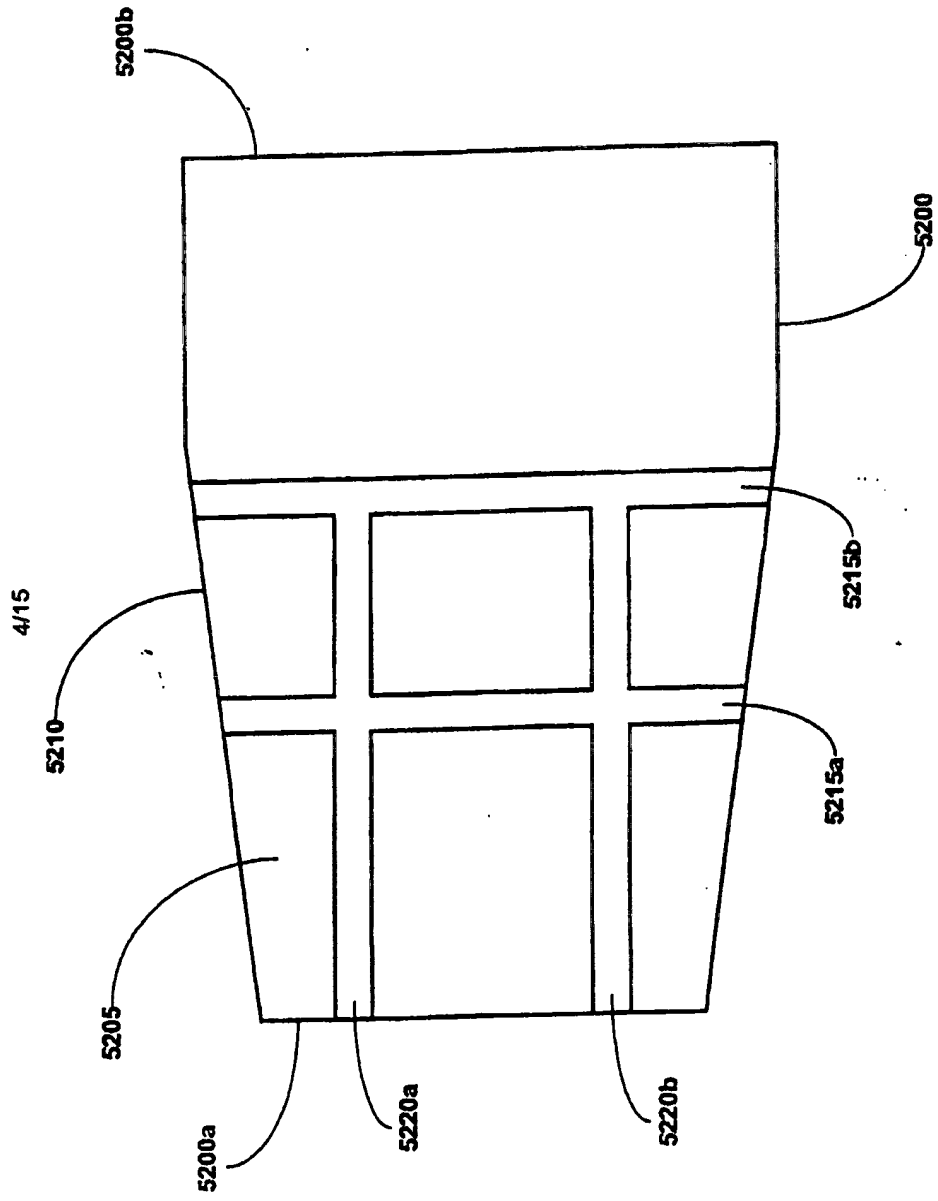


FIGURE 5

5/15

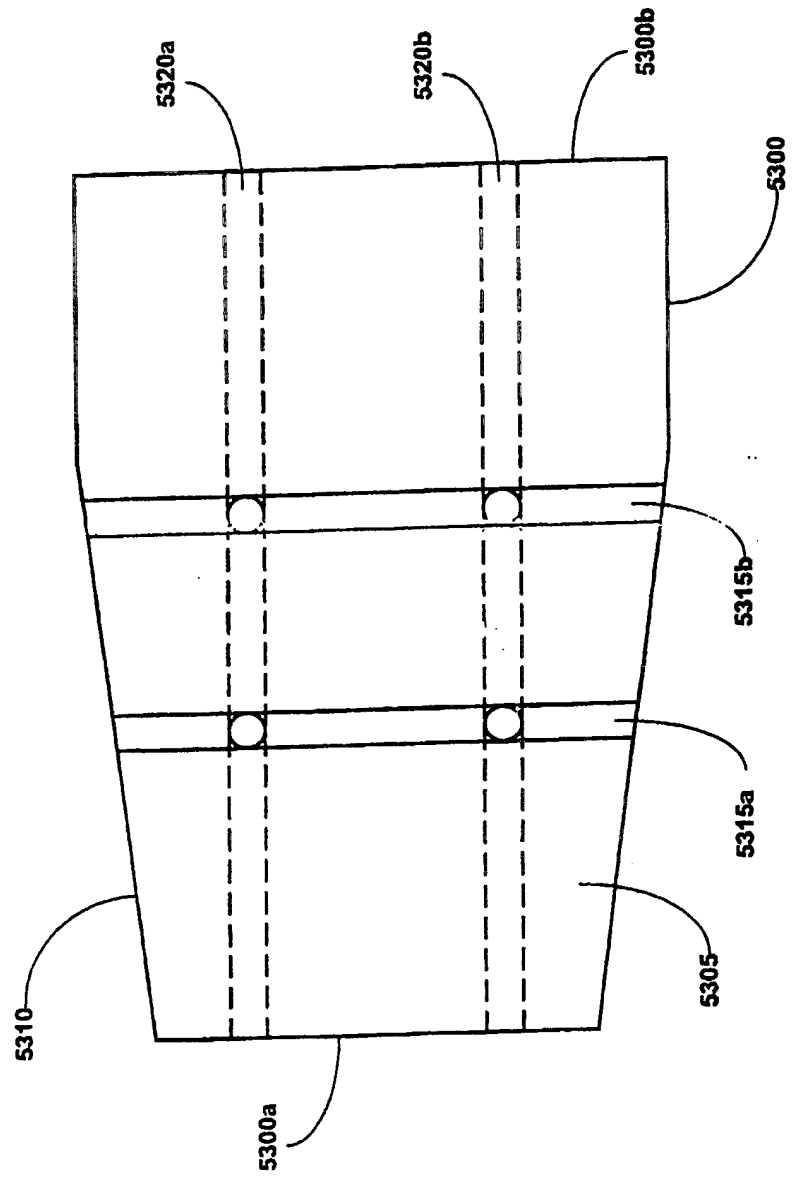


FIGURE 6

6/15

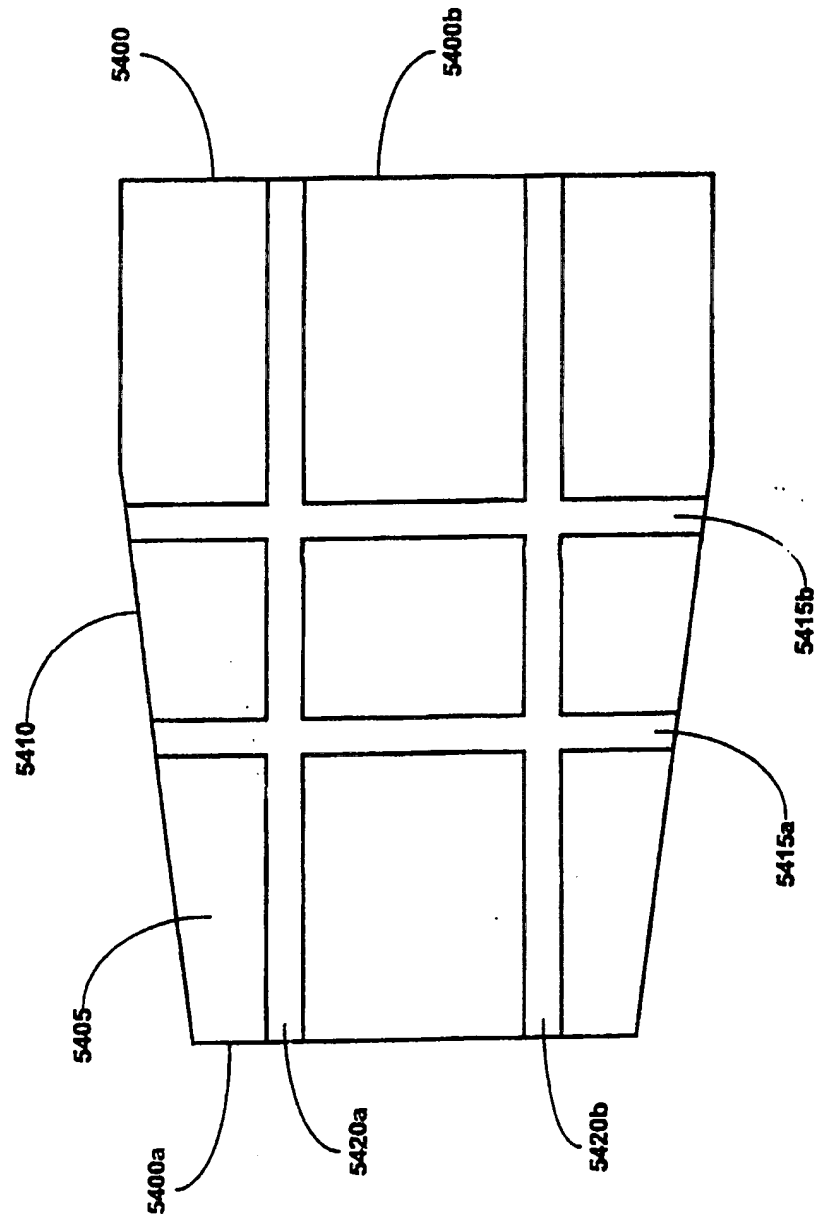


FIGURE 7

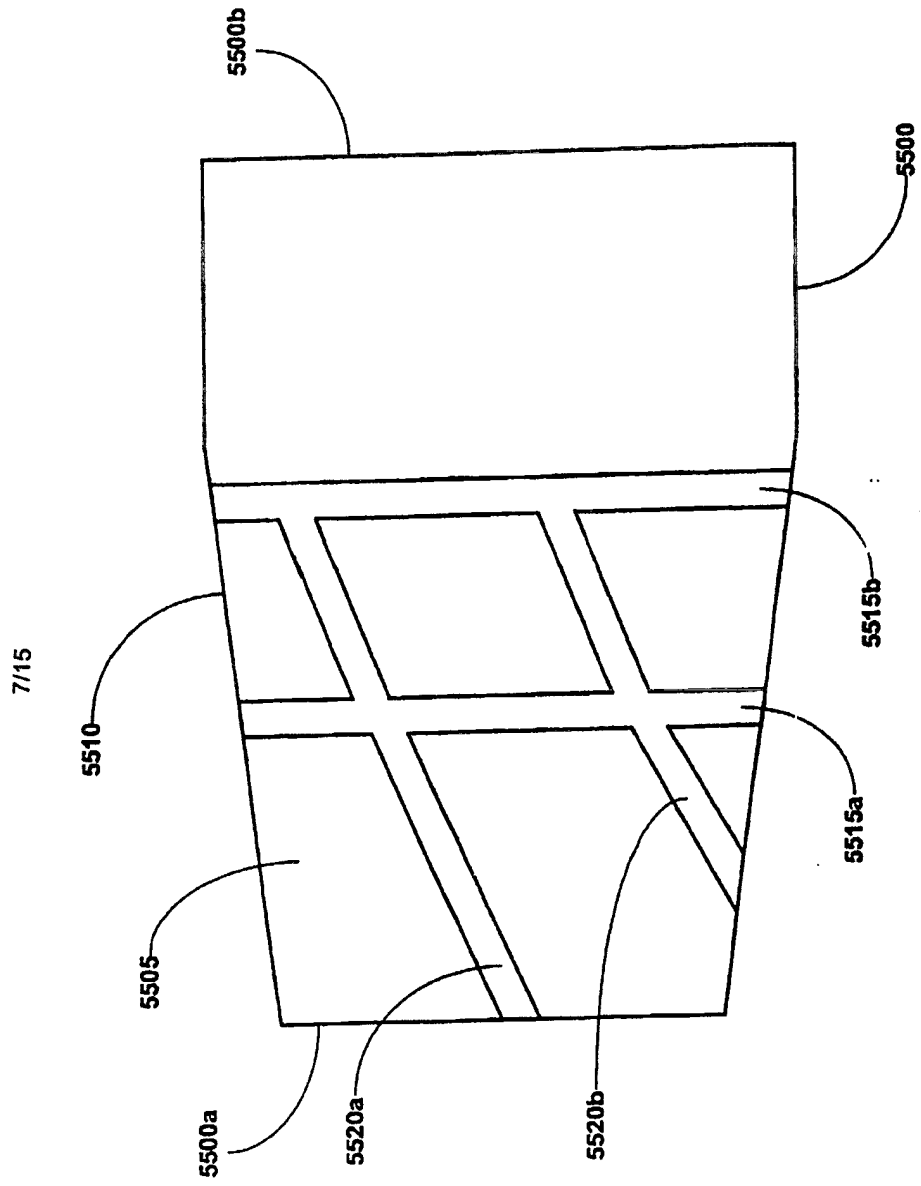


FIGURE 8

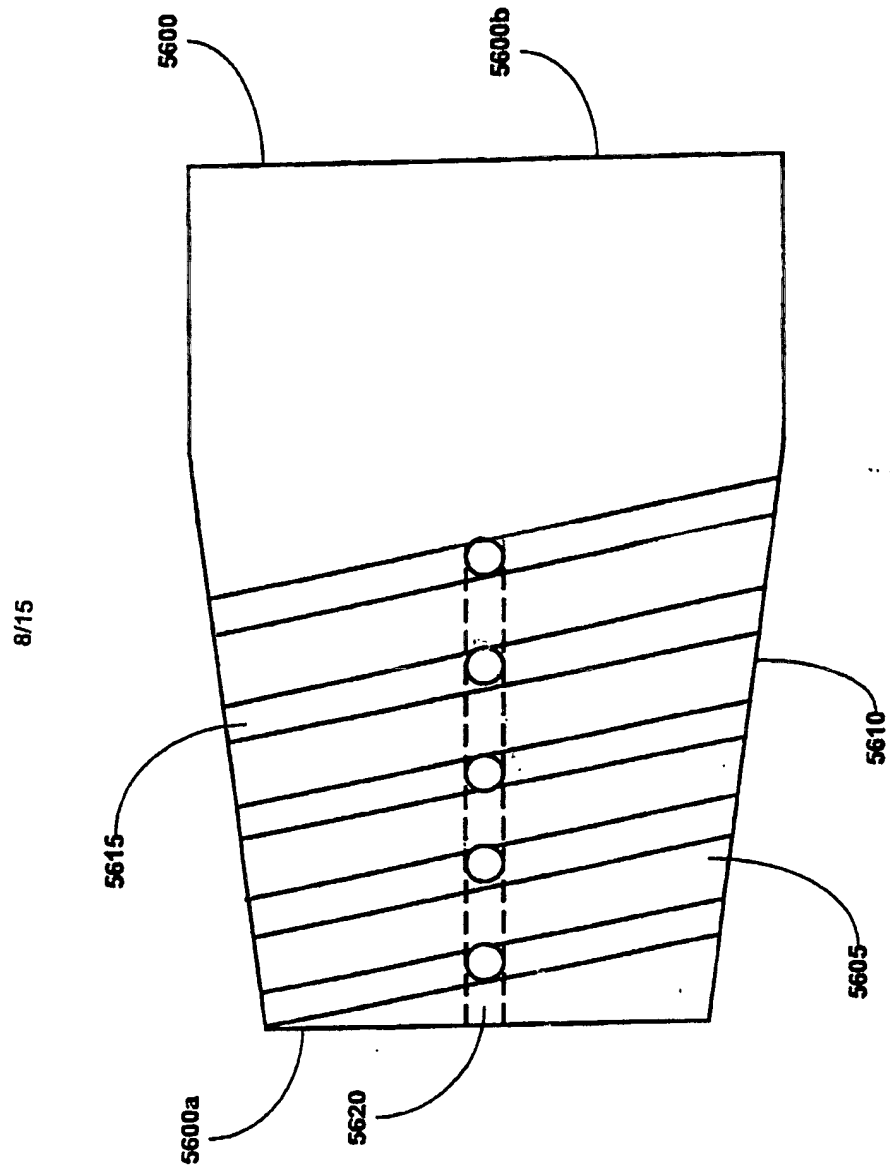


FIGURE 9

8/15

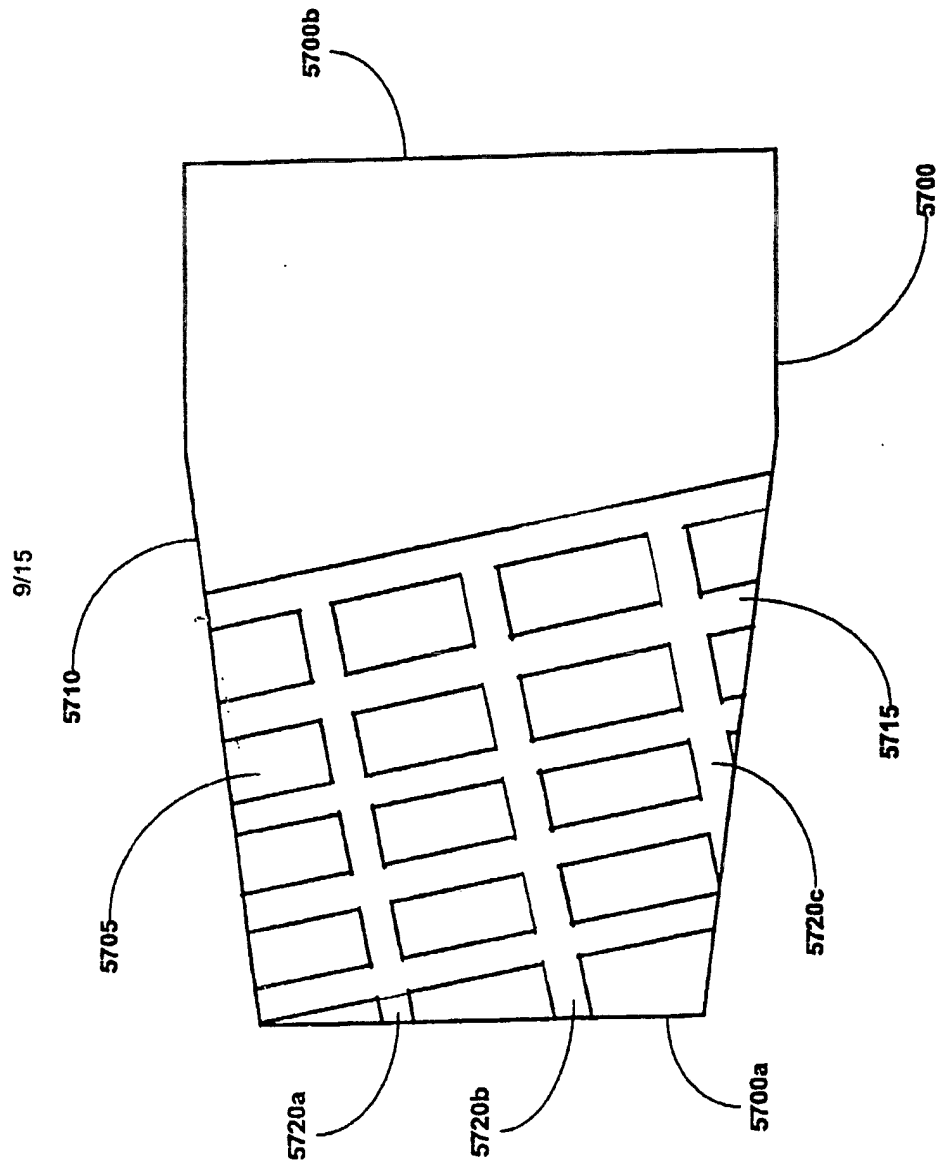


FIGURE 10

10/15

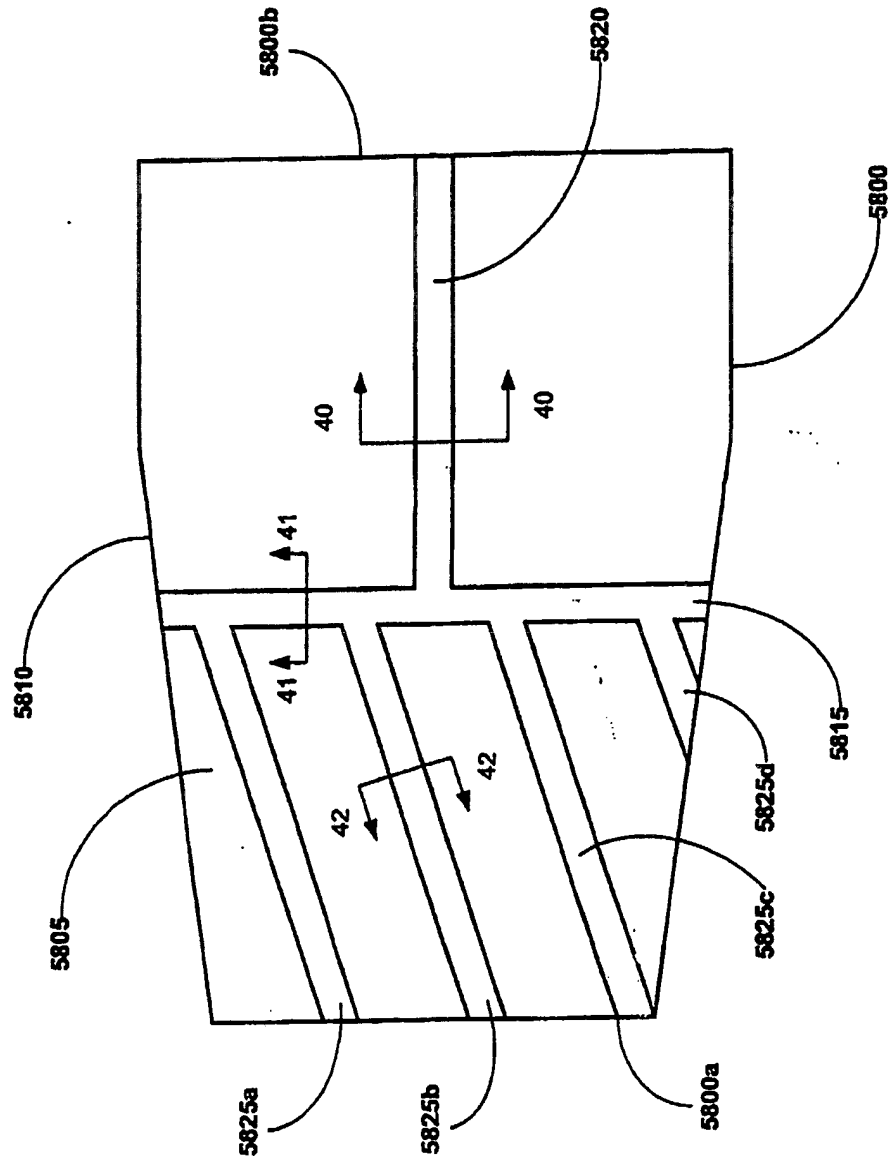


FIGURE 11

11/15

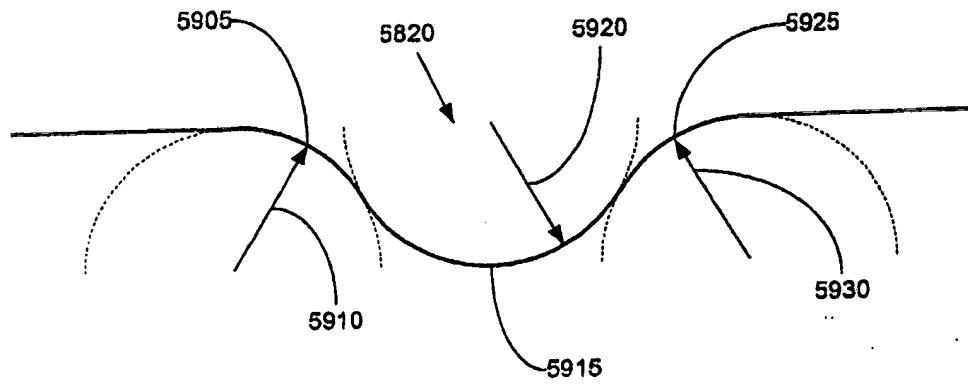


FIGURE 12

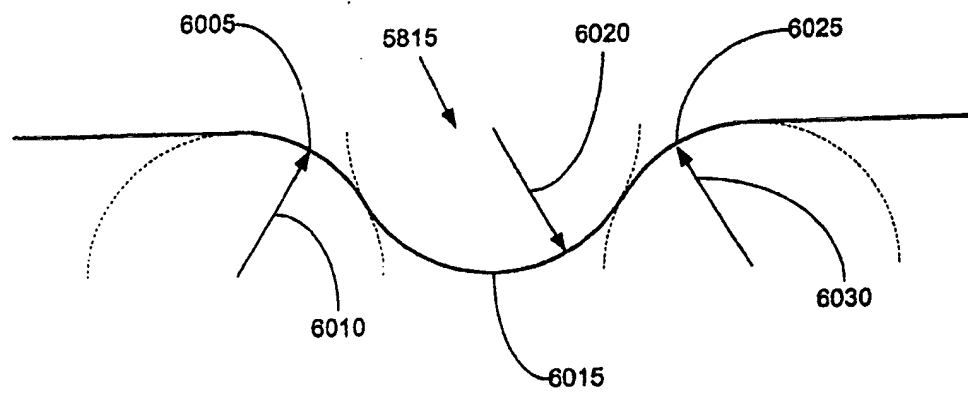


FIGURE 13

12/15

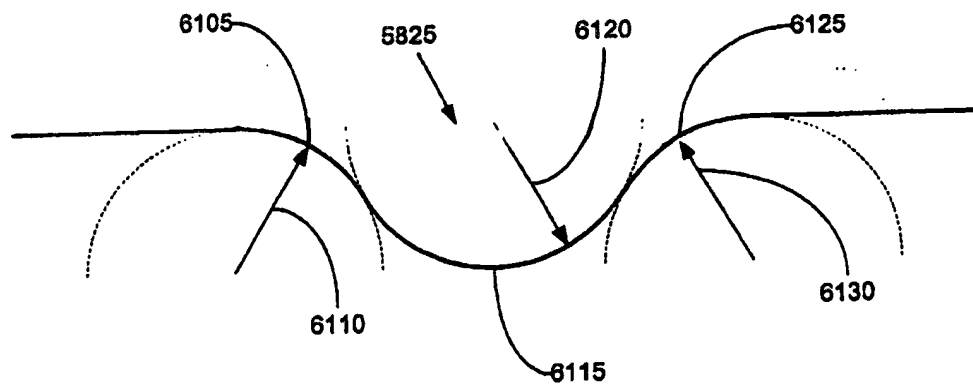
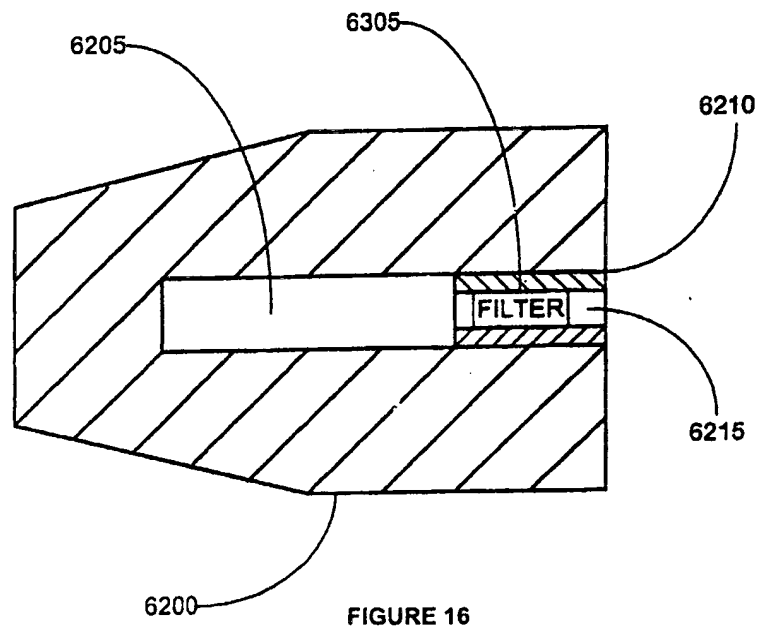
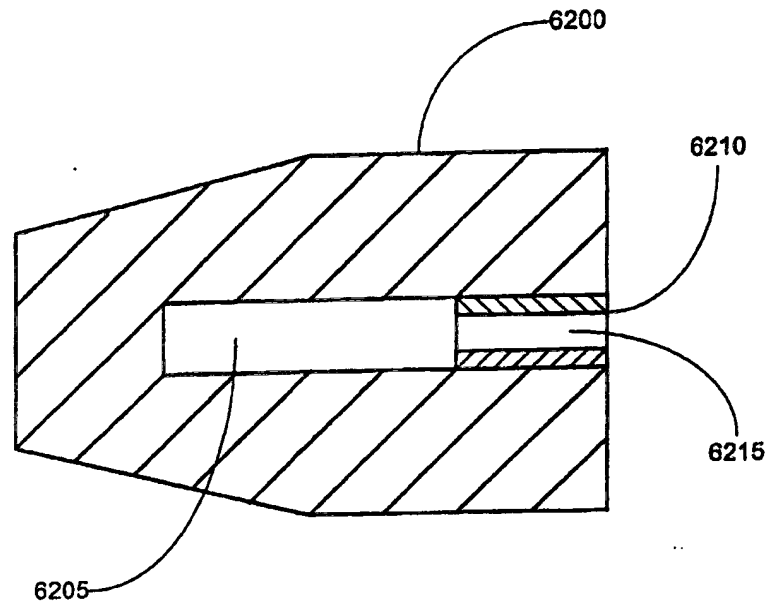


FIGURE 14

13/15



14/15

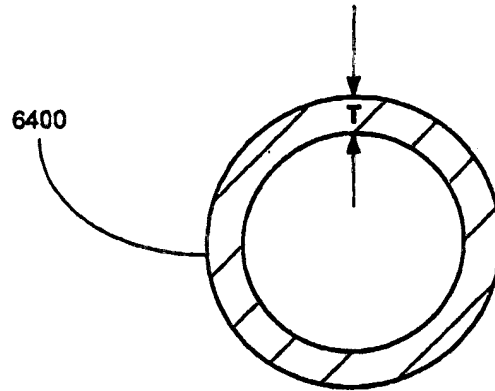


FIGURE 17

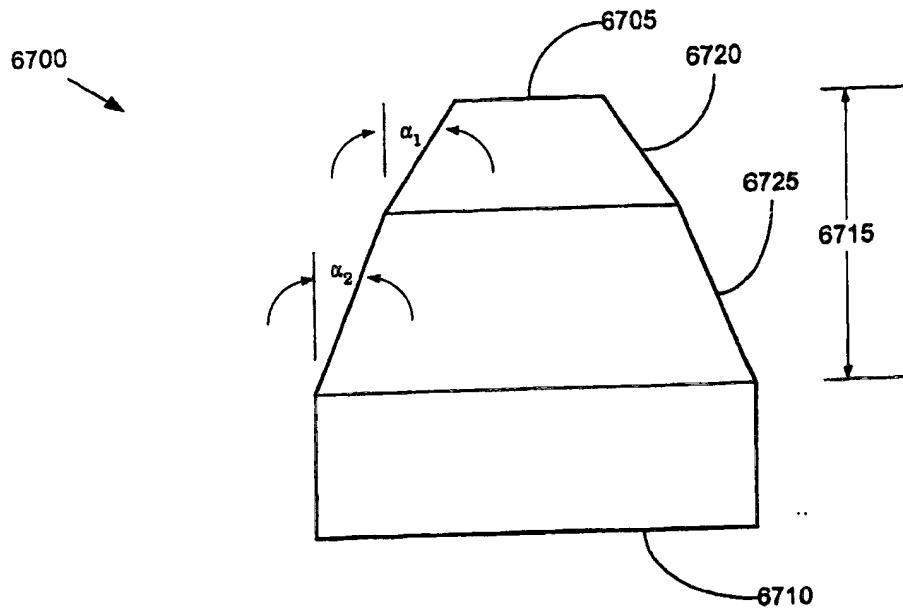
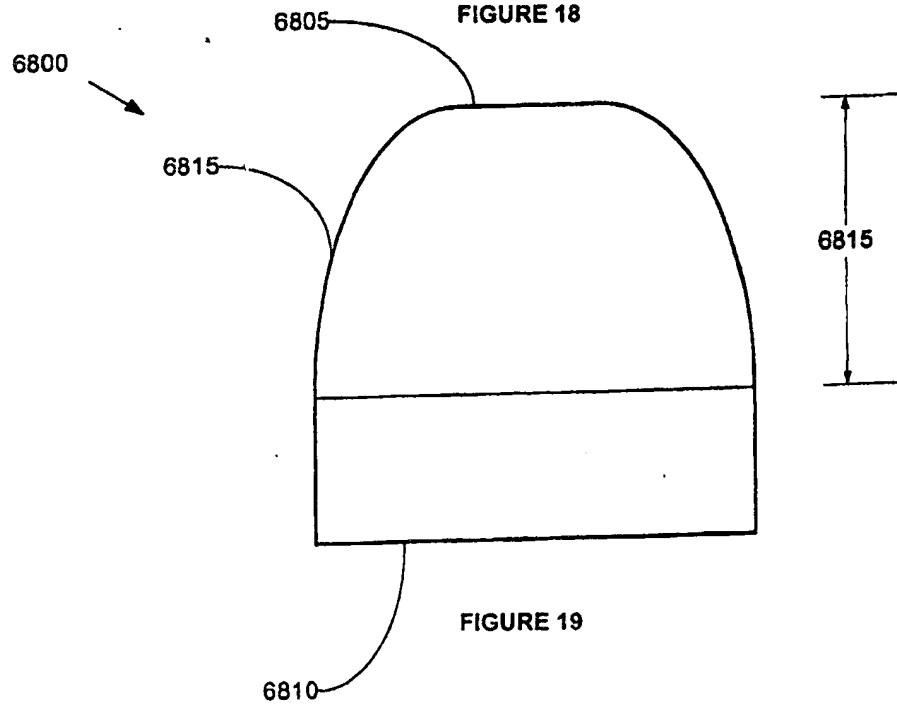


FIGURE 18



2392932

A PARABLOID EXPANSION CONE

Cross Reference To Related Applications

5 This application claims the benefit of the filing date of U.S. provisional patent application serial no. 60/143,039, attorney docket no. 25791.26, filed on July 9, 1999, and U.S. provisional patent application serial no. 60/146,203, attorney docket no. 25791.25, filed on July 29, 1999.

10 This application is related to the following co-pending applications: provisional patent application number 60/108,558, filed 11/16/1998, provisional patent application number 60/111,293, filed 12/7/1998, provisional patent application number 60/119,611, filed 2/11/1999, provisional patent application number 60/121,702, filed 2/25/1999, provisional patent application number 60/121,907, filed 2/26/1999, provisional patent application number 60/124,042, filed 3/11/1999, provisional patent application number 60/131,106, filed 4/26/1999, provisional patent application number 60/137,998, filed 6/7/1999, and provisional patent application number 60/143,039, attorney docket number 25791.26, filed on 7/9/1999.

Background of the Invention

This invention relates generally to a paraboloid expansion cone.

20 Conventionally, when a wellbore is created, a number of casings are installed in the borehole to prevent collapse of the borehole wall and to prevent undesired outflow of drilling fluid into the formation or inflow of fluid from the formation into the borehole. The borehole is drilled in intervals whereby a casing which is to be installed in a lower borehole interval is lowered through a previously installed casing of an upper borehole interval. As a consequence of this procedure the casing of the lower interval is of 25 smaller diameter than the casing of the upper interval. Thus, the casings are in a nested arrangement with casing diameters decreasing in downward direction. Cement annuli are provided between the outer surfaces of the casings and the borehole wall to seal the casings from the borehole wall. As a consequence of this nested arrangement a relatively large borehole diameter is required at the upper part of the wellbore. Such 30 a large borehole diameter involves increased costs due to heavy casing handling equipment, large drill bits and increased volumes of drilling fluid and drill cuttings. Moreover, increased drilling rig time is involved due to required cement pumping, cement hardening, required equipment changes due to large variations in hole diameters drilled in the course of the well, and the large volume of cuttings drilled and 35 removed.

Conventionally, at the surface end of the wellbore, a wellhead is formed that typically includes a surface casing, a number of production and/or drilling spools, valving, and a Christmas tree. Typically the wellhead further includes a concentric arrangement of casings including a production casing and one or more intermediate casings. The casings are typically supported using load bearing slips positioned above the ground. The conventional design and construction of wellheads is expensive and complex.

Conventionally, a wellbore casing cannot be formed during the drilling of a wellbore. Typically, the wellbore is drilled and then a wellbore casing is formed in the newly drilled section of the wellbore. This delays the completion of a well.

The present invention is directed to overcoming one or more of the limitations of the existing procedures for forming wellbores and wellheads.

Summary of the Invention

According to the present invention, there is provided an expansion cone for radially expanding a tubular member, comprising a paraboloid expansion cone body.

Preferably, the angle of attack of the outer surface of the paraboloid expansion cone body increases in a continuous manner from one end of the paraboloid expansion cone body to the opposite end of the paraboloid expansion cone body.

Preferably, at least a portion of the paraboloid expansion cone body has an angle of attack of 25° .

Preferably, the expansion cone further comprises a lubricant on an outer surface of the paraboloid expansion cone body.

Preferably, one or more grooves are formed in an outer surface of the paraboloid expansion cone body

Preferably, the expansion cone further comprises one or more axial flow passages defined within the paraboloid expansion cone body.

Preferably, the grooves are circumferential grooves. Alternatively, the grooves may be spiral grooves.

Preferably, the grooves are concentrated around an axial midpoint of the paraboloid expansion cone body

Preferably, the axial flow passages comprise axial grooves which are spaced apart by at least about 3 inches in the circumferential direction.

Preferably, the expansion cone further comprises flow passages, which are positioned within the paraboloid expansion cone body

Preferably, the flow passages are coupled to one or more grooves.

Preferably, one or more of the flow passages include inserts having restricted flow passages

Preferably, one or more of the flow passages include filters.

Preferably, the cross-sectional area of the grooves and axial flow passages ranges from $1.29 \times 10^{-7} \text{ m}^2$ to $3.226 \times 10^{-6} \text{ m}^2$ ($2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$).

Preferably, the grooves include; a flow channel having a first radius of curvature, a first shoulder positioned on one side of the flow channel having a second radius of curvature, and a second shoulder positioned on the other side of the flow channel having a third radius of curvature.

10 Preferably, the first, second and third radii of curvature are substantially equal.

Preferably, the axial flow passages include; a flow channel having a first radius of curvature, a first shoulder positioned on one side of the flow channel having a second radius of curvature, and a second shoulder positioned on the other side of the flow channel having a third radius of curvature.

15 Preferably, the first, second and third radii of curvature are substantially equal. Alternatively, the second radius of curvature is greater than the third radius of curvature.

Brief Description of the Drawings

20 FIG. 1 is a partial cross-sectional illustration of an expansion mandrel expanding a tubular member.

FIG. 2 is a graphical illustration of the relationship between propagation pressure and the angle of attack of the expansion mandrel.

25 FIG. 3 is a fragmentary cross-sectional illustration of the lubrication of the interface between an expansion mandrel and a tubular member during the radial expansion process.

FIG. 4 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

30 FIG. 5 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

35 FIG. 6 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 7 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 8 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 9 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 10 is an illustration of an embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 11 is an illustration of a preferred embodiment of an expansion mandrel including a system for lubricating the interface between the expansion mandrel and a tubular member during the radial expansion of the tubular member.

FIG. 12 is a cross-sectional illustration of the first axial groove of the expansion mandrel of FIG. 11.

FIG. 13 is a cross-sectional illustration of the circumferential groove of the expansion mandrel of FIG. 11.

FIG. 14 is a cross-sectional illustration of one of the second axial grooves of the expansion mandrel of FIG. 11.

FIG. 15 is a cross sectional illustration of an embodiment of an expansion mandrel including internal flow passages having inserts for adjusting the flow of lubricant fluids.

FIG. 16 is a cross sectional illustration of the expansion mandrel of FIG.15 further including an insert having a filter for filtering out foreign materials from the lubricant fluids.

FIG. 17 is a cross sectional illustration of a preferred embodiment of an expandable tubular for use in forming and/or repairing a wellbore casing, pipeline, or foundation support.

FIG. 18 is an illustration of an embodiment of an expansion cone optimally adapted to radially expand a tubular member.

FIG. 19 is an illustration of another embodiment of an expansion cone optimally adapted to radially expand a tubular member.

Referring to Figs. 1 and 2, the optimal relationship between the angle of attack of an expansion mandrel and the minimally required propagation pressure during the expansion of a tubular member will now be described. As illustrated in Fig. 1, during the radial expansion of a tubular member 4100 by an expansion mandrel 4105, the expansion mandrel 4105 is displaced in the axial direction. The angle of attack α of the conical surface 4110 of the expansion mandrel 4105 directly affects the required propagation pressure P_{PR} necessary to radially expand the tubular member 4100. Referring to Fig. 2, for typical grades of materials and typical geometries, the propagation pressure P_{PR} is minimized for an angle of attack of approximately 25 degrees. Furthermore, the optimal range of the angle of attack α ranges from about 10 to 30 degrees in order to minimize the range of required minimum propagation pressure P_{PR} .

Referring to Fig. 3, the lubrication of the interface between an expansion mandrel and a tubular member during the radial expansion process will now be described. As illustrated in Fig. 3, during the radial expansion process, an expansion cone 5000 radially expands a tubular member 5005 by moving in an axial direction 5010 relative to the tubular member 5005. The interface between the outer surface 5010 of the tapered portion 5015 of the expansion cone 5000 and the inner surface 5020 of the tubular member 5005 includes a leading edge portion 5025 and a trailing edge portion 5030.

During the radial expansion process, the leading edge portion 5025 is preferably lubricated by the presence of lubricating fluids provided ahead of the expansion cone 5000. However, because the radial clearance between the expansion cone 5000 and the tubular member 5005 in the trailing edge portion 5030 during the radial expansion process is typically extremely small, and the operating contact pressures between the tubular member 5005 and the expansion mandrel 5000 are extremely high, the quantity of lubricating fluid provided to the trailing edge portion 5030 is typically greatly reduced. In typical radial expansion operations, this reduction in lubrication in the trailing edge portion 5030 increases the forces required to radially expand the tubular member 5005.

Referring to Fig. 4, an embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 4, an expansion cone 5100, having a front end 5100a and a rear end 5100b, includes a tapered portion 5105 having an outer surface 5110, one or more circumferential grooves 5115a and 5115b, and one more internal flow passages 5120a and 5120b.

In a preferred embodiment, the circumferential grooves 5115 are fluidly coupled to the internal flow passages 5120. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5100a of the expansion cone 5100 into the circumferential grooves 5115. Thus, the trailing edge portion of the interface between the expansion cone 5100 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the lubricating fluids are injected into the internal flow passages 5120 using a fluid conduit that is coupled to the tapered end 5105 of the expansion cone 5100. Alternatively, lubricating fluids are provided for the internal flow passages 5120 using a supply of lubricating fluids provided adjacent to the front 5100a of the expansion cone 5100.

In a preferred embodiment, the expansion cone 5100 includes a plurality of circumferential grooves 5115. In a preferred embodiment, the cross sectional area of the circumferential grooves 5115 range from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5100 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5100 includes circumferential grooves 5115 concentrated about the axial midpoint of the tapered portion 5105 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5100 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5115 are equally spaced along the trailing edge portion of the expansion cone 5100 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5100 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5100 includes a plurality of flow passages 5120 coupled to each of the circumferential grooves 5115. In a preferred embodiment, the cross-sectional area of the flow passages 5120 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5100 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5115 is greater than the cross sectional area of the flow passage 5120 in order to minimize resistance to fluid flow.

Referring to Fig. 5, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 5, an expansion cone 5200, having a front end

5200a and a rear end 5200b, includes a tapered portion 5205 having an outer surface 5210, one or more circumferential grooves 5215a and 5215b, and one or more axial grooves 5220a and 5220b.

In a preferred embodiment, the circumferential grooves 5215 are fluidly coupled to the axial grooves 5220. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5200a of the expansion cone 5200 into the circumferential grooves 5215. Thus, the trailing edge portion of the interface between the expansion cone 5200 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the axial grooves 5220 are provided with lubricating fluid using a supply of lubricating fluid positioned proximate the front end 5200a of the expansion cone 5200. In a preferred embodiment, the circumferential grooves 5215 are concentrated about the axial midpoint of the tapered portion 5205 of the expansion cone 5200 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5200 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5215 are equally spaced along the trailing edge portion of the expansion cone 5200 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5200 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5200 includes a plurality of circumferential grooves 5215. In a preferred embodiment, the cross sectional area of the circumferential grooves 5215 range from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5200 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5200 includes a plurality of axial grooves 5220 coupled to each of the circumferential grooves 5215. In a preferred embodiment, the cross sectional area of the axial grooves 5220 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5200 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5215 is greater than the cross sectional area of the axial grooves 5220 in order to minimize resistance to fluid flow. In a preferred embodiment, the axial grooves 5220 are spaced apart in the circumferential direction by at least about 3 inches in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 6, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 6, an expansion cone 5300, having a front end 5300a and a rear end 5300b, includes a tapered portion 5305 having an outer surface 5310, one or more circumferential grooves 5315a and 5315b, and one or more internal flow passages 5320a and 5320b.

In a preferred embodiment, the circumferential grooves 5315 are fluidly coupled to the internal flow passages 5320. In this manner, during the radial expansion process, lubricating fluids are transmitted from the areas in front of the front 5300a and/or behind the rear 5300b of the expansion cone 5300 into the circumferential grooves 5315. Thus, the trailing edge portion of the interface between the expansion cone 5300 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. Furthermore, the lubricating fluids also preferably pass to the area in front of the expansion cone. In this manner, the area adjacent to the front 5300a of the expansion cone 5300 is cleaned of foreign materials. In a preferred embodiment, the lubricating fluids are injected into the internal flow passages 5320 by pressurizing the area behind the rear 5300b of the expansion cone 5300 during the radial expansion process.

In a preferred embodiment, the expansion cone 5300 includes a plurality of circumferential grooves 5315. In a preferred embodiment, the cross sectional area of the circumferential grooves 5315 ranges from about 2×10^{-4} in² to 5×10^{-2} in² respectively, in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5300 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5300 includes circumferential grooves 5315 that are concentrated about the axial midpoint of the tapered portion 5305 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5300 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5315 are equally spaced along the trailing edge portion of the expansion cone 5300 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5300 and a tubular member during the radial expansion process.

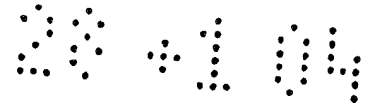
In a preferred embodiment, the expansion cone 5300 includes a plurality of flow passages 5320 coupled to each of the circumferential grooves 5315. In a preferred embodiment, the flow passages 5320 fluidly couple the front end 5300a and the rear

end 5300b of the expansion cone 5300. In a preferred embodiment, the cross-sectional area of the flow passages 5320 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5300 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5315 is greater than the cross-sectional area of the flow passages 5320 in order to minimize resistance to fluid flow.

Referring to Fig. 7, an embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 7, an expansion cone 5400, having a front end 5400a and a rear end 5400b, includes a tapered portion 5405 having an outer surface 5410, one or more circumferential grooves 5415a and 5415b, and one or more axial grooves 5420a and 5420b.

In a preferred embodiment, the circumferential grooves 5415 are fluidly coupled to the axial grooves 5420. In this manner, during the radial expansion process, lubricating fluids are transmitted from the areas in front of the front 5400a and/or behind the rear 5400b of the expansion cone 5400 into the circumferential grooves 5415. Thus, the trailing edge portion of the interface between the expansion cone 5400 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. Furthermore, in a preferred embodiment, pressurized lubricating fluids pass from the fluid passages 5420 to the area in front of the front 5400a of the expansion cone 5400. In this manner, the area adjacent to the front 5400a of the expansion cone 5400 is cleaned of foreign materials. In a preferred embodiment, the lubricating fluids are injected into the internal flow passages 5420 by pressurizing the area behind the rear 5400b expansion cone 5400 during the radial expansion process.

In a preferred embodiment, the expansion cone 5400 includes a plurality of circumferential grooves 5415. In a preferred embodiment, the cross sectional area of the circumferential grooves 5415 range from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5400 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5400 includes circumferential grooves 5415 that are concentrated about the axial midpoint of the tapered portion 5405 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5400 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5415 are equally spaced along the



trailing edge portion of the expansion cone 5400 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5400 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5400 includes a plurality of axial grooves 5420 coupled to each of the circumferential grooves 5415. In a preferred embodiment, the axial grooves 5420 fluidically couple the front end and the rear end of the expansion cone 5400. In a preferred embodiment, the cross sectional area of the axial grooves 5420 range from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$, respectively, in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5400 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5415 is greater than the cross sectional area of the axial grooves 5420 in order to minimize resistance to fluid flow. In a preferred embodiment, the axial grooves 5420 are spaced apart in the circumferential direction by at least about 3 inches in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 8, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 8, an expansion cone 5500, having a front end 5500a and a rear end 5500b, includes a tapered portion 5505 having an outer surface 5510, one or more circumferential grooves 5515a and 5515b, and one or more axial grooves 5520a and 5520b.

In a preferred embodiment, the circumferential grooves 5515 are fluidically coupled to the axial grooves 5520. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5500a of the expansion cone 5500 into the circumferential grooves 5515. Thus, the trailing edge portion of the interface between the expansion cone 5500 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the lubricating fluids are injected into the axial grooves 5520 using a fluid conduit that is coupled to the tapered end 3205 of the expansion cone 3200.

In a preferred embodiment, the expansion cone 5500 includes a plurality of circumferential grooves 5515. In a preferred embodiment, the cross sectional area of the circumferential grooves 5515 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5500 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5500 includes circumferential grooves 5515

that are concentrated about the axial midpoint of the tapered portion 5505 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5500 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5515 are equally spaced along the trailing edge portion of the expansion cone 5500 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5500 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5500 includes a plurality of axial grooves 5520 coupled to each of the circumferential grooves 5515. In a preferred embodiment, the axial grooves 5520 intersect each of the circumferential grooves 5515 at an acute angle. In a preferred embodiment, the cross sectional area of the axial grooves 5520 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5500 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential grooves 5515 is greater than the cross sectional area of the axial grooves 5520. In a preferred embodiment, the axial grooves 5520 are spaced apart in the circumferential direction by at least about 3 inches in order to optimally provide lubrication during the radial expansion process. In a preferred embodiment, the axial grooves 5520 intersect the longitudinal axis of the expansion cone 5500 at a larger angle than the angle of attack of the tapered portion 5505 in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 9, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 9, an expansion cone 5600, having a front end 5600a and a rear end 5600b, includes a tapered portion 5605 having an outer surface 5610, a spiral circumferential groove 5615, and one or more internal flow passages 5620.

In a preferred embodiment, the circumferential groove 5615 is fluidically coupled to the internal flow passage 5620. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5600a of the expansion cone 5600 into the circumferential groove 5615. Thus, the trailing edge portion of the interface between the expansion cone 5600 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the

lubricating fluids are injected into the internal flow passage 5620 using a fluid conduit that is coupled to the tapered end 5605 of the expansion cone 5600.

In a preferred embodiment, the expansion cone 5600 includes a plurality of spiral circumferential grooves 5615. In a preferred embodiment, the cross sectional area of the circumferential groove 5615 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5600 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5600 includes circumferential grooves 5615 that are concentrated about the axial midpoint of the tapered portion 5605 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5600 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5615 are equally spaced along the trailing edge portion of the expansion cone 5600 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5600 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5600 includes a plurality of flow passages 5620 coupled to each of the circumferential grooves 5615. In a preferred embodiment, the cross-sectional area of the flow passages 5620 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5600 and a tubular member during the radial expansion process. In a preferred embodiment, the cross sectional area of the circumferential groove 5615 is greater than the cross sectional area of the flow passage 5620 in order to minimize resistance to fluid flow.

Referring to Fig. 10, another embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 10, an expansion cone 5700, having a front end 5700a and a rear end 5700b, includes a tapered portion 5705 having an outer surface 5710, a spiral circumferential groove 5715, and one or more axial grooves 5720a, 5720b and 5720c.

In a preferred embodiment, the circumferential groove 5715 is fluidically coupled to the axial grooves 5720. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 5700a of the expansion cone 5700 into the circumferential groove 5715. Thus, the trailing edge portion of the interface between the expansion cone 5700 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the

lubricating fluids are injected into the axial grooves 5720 using a fluid conduit that is coupled to the tapered end 5705 of the expansion cone 5700.

In a preferred embodiment, the expansion cone 5700 includes a plurality of spiral circumferential grooves 5715. In a preferred embodiment, the cross sectional area of the circumferential grooves 5715 range from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5700 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5700 includes circumferential grooves 5715 concentrated about the axial midpoint of the tapered portion 5705 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5700 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5715 are equally spaced along the trailing edge portion of the expansion cone 5700 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5700 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5700 includes a plurality of axial grooves 5720 coupled to each of the circumferential grooves 5715. In a preferred embodiment, the cross sectional area of the axial grooves 5720 range from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5700 and a tubular member during the radial expansion process. In a preferred embodiment, the axial grooves 5720 intersect the circumferential grooves 5715 in a perpendicular manner. In a preferred embodiment, the cross sectional area of the circumferential groove 5715 is greater than the cross sectional area of the axial grooves 5720 in order to minimize resistance to fluid flow. In a preferred embodiment, the circumferential spacing of the axial grooves is greater than about 3 inches in order to optimally provide lubrication during the radial expansion process. In a preferred embodiment, the axial grooves 5720 intersect the longitudinal axis of the expansion cone at an angle greater than the angle of attack of the tapered portion 5705 in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 11, a preferred embodiment of a system for lubricating the interface between an expansion cone and a tubular member during the expansion process will now be described. As illustrated in Fig. 11, an expansion cone 5800, having a front end 5800a and a rear end 5800b, includes a tapered portion 5805 having an outer surface 5810, a circumferential groove 5815, a first axial groove 5820, and one or more second axial grooves 5825a, 5825b, 5825c and 5825d.

In a preferred embodiment, the circumferential groove 5815 is fluidically coupled to the axial grooves 5820 and 5825. In this manner, during the radial expansion process, lubricating fluids are preferably transmitted from the area behind the back 5800b of the expansion cone 5800 into the circumferential groove 5815. Thus, the trailing edge portion of the interface between the expansion cone 5800 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. In a preferred embodiment, the lubricating fluids are injected into the first axial groove 5820 by pressurizing the region behind the back 5800b of the expansion cone 5800. In a preferred embodiment, the lubricant is further transmitted into the second axial grooves 5825 where the lubricant preferably cleans foreign materials from the tapered portion 5805 of the expansion cone 5800.

In a preferred embodiment, the expansion cone 5800 includes a plurality of circumferential grooves 5815. In a preferred embodiment, the cross sectional area of the circumferential groove 5815 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process. In a preferred embodiment, the expansion cone 5800 includes circumferential grooves 5815 concentrated about the axial midpoint of the tapered portion 5805 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process. In a preferred embodiment, the circumferential grooves 5815 are equally spaced along the trailing edge portion of the expansion cone 5800 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process.

In a preferred embodiment, the expansion cone 5800 includes a plurality of first axial grooves 5820 coupled to each of the circumferential grooves 5815. In a preferred embodiment, the first axial grooves 5820 extend from the back 5800b of the expansion cone 5800 and intersect the circumferential groove 5815. In a preferred embodiment, the cross sectional area of the first axial groove 5820 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process. In a preferred embodiment, the first axial groove 5820 intersects the circumferential groove 5815 in a perpendicular manner. In a preferred embodiment, the cross sectional area of the circumferential groove 5815 is greater than the cross sectional area of the first axial groove 5820 in order to minimize

resistance to fluid flow. In a preferred embodiment, the circumferential spacing of the first axial grooves 5820 is greater than about 3 inches in order to optimally provide lubrication during the radial expansion process.

In a preferred embodiment, the expansion cone 5800 includes a plurality of second axial grooves 5825 coupled to each of the circumferential grooves 5815. In a preferred embodiment, the second axial grooves 5825 extend from the front 5800a of the expansion cone 5800 and intersect the circumferential groove 5815. In a preferred embodiment, the cross sectional area of the second axial grooves 5825 ranges from about $2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$ in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 5800 and a tubular member during the radial expansion process. In a preferred embodiment, the second axial grooves 5825 intersect the circumferential groove 5815 in a perpendicular manner. In a preferred embodiment, the cross sectional area of the circumferential groove 5815 is greater than the cross sectional area of the second axial grooves 5825 in order to minimize resistance to fluid flow. In a preferred embodiment, the circumferential spacing of the second axial grooves 5825 is greater than about 3 inches in order to optimally provide lubrication during the radial expansion process. In a preferred embodiment, the second axial grooves 5825 intersect the longitudinal axis of the expansion cone 5800 at an angle greater than the angle of attack of the tapered portion 5805 in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 12, in a preferred embodiment, the first axial groove 5820 includes a first portion 5905 having a first radius of curvature 5910, a second portion 5915 having a second radius of curvature 5920, and a third portion 5925 having a third radius of curvature 5930. In a preferred embodiment, the radius of curvatures, 5910, 5920 and 5930 are substantially equal. In an exemplary embodiment, the radius of curvatures, 5910, 5920 and 5930 are all substantially equal to 0.0625 inches.

Referring to Fig. 13, in a preferred embodiment, the circumferential groove 5815 includes a first portion 6005 having a first radius of curvature 6010, a second portion 6015 having a second radius of curvature 6020, and a third portion 6025 having a third radius of curvature 6030. In a preferred embodiment, the radius of curvatures, 6010, 6020 and 6030 are substantially equal. In an exemplary embodiment, the radius of curvatures, 6010, 6020 and 6030 are all substantially equal to 0.125 inches.

Referring to Fig. 14, in a preferred embodiment, the second axial groove 5825 includes a first portion 6105 having a first radius of curvature 6110, a second portion 6115 having a second radius of curvature 6120, and a third portion 6125 having a third radius of curvature 6130. In a preferred embodiment, the first radius of curvature 6110

is greater than the third radius of curvature 6130. In an exemplary embodiment, the first radius of curvature 6110 is equal to 0.5 inches, the second radius of curvature 6120 is equal to 0.0625 inches, and the third radius of curvature 6130 is equal to 0.125 inches.

5 Referring to Fig. 15, an embodiment of an expansion mandrel 6200 includes an internal flow passage 6205 having an insert 6210 including a flow passage 6215. In a preferred embodiment, the cross sectional area of the flow passage 6215 is less than the cross sectional area of the flow passage 6205. More generally, in a preferred embodiment, a plurality of inserts 6210 are provided, each with different sizes of flow
10 passages 6215. In this manner, the flow passage 6215 is machined to a standard size, and the lubricant supply is varied by using different sized inserts 6210. In a preferred embodiment, the teachings of the expansion mandrel 6200 are incorporated into the expansion mandrels 5100, 5300, and 5600.

Referring to Fig. 16, in a preferred embodiment, the insert 6210 includes a filter
15 6305 for filtering particles and other foreign materials from the lubricant that passes into the flow passage 6205. In this manner, the foreign materials are prevented from clogging the flow passage 6205 and other flow passages within the expansion mandrel 6200.

In a preferred embodiment, the one or more of the lubrication systems and
20 elements of the mandrels 5100, 5200, 5300, 5400, 5500, 5600, 5700, 5800 and/or 5900 are incorporated into the methods and apparatus for expanding tubular members described above with reference to Figs. 1 and 2. In this manner, the amount of force required to radially expand a tubular member in the formation and/or repair of a wellbore casing, pipeline, or structural support is significantly reduced. Furthermore,
25 the increased lubrication provided to the trail edge portion of the mandrel greatly reduces the amount of galling or seizure caused by the interface between the mandrel and the tubular member during the radial expansion process thereby permitting larger continuous sections of tubulars to be radially expanded in a single continuous operation. Thus, use of the mandrels 5100, 5200, 5300, 5400, 5500, 5600, 5700, 5800
30 and/or 5900 reduces the operating pressures required for radial expansion and thereby reduces the sizes of the required hydraulic pumps and related equipment. In addition, failure, bursting, and/or buckling of tubular members during the radial expansion process is significantly reduced, and the success ratio of the radial expansion process is greatly increased.

35 In laboratory tests, a regular expansion cone, without any lubrication grooves and flow passages, and the expansion cone 5100 were both used to radially expand

identical coiled tubular members, each having an outside diameter of 3 ½ inches. The following tables summarizes the results of this laboratory test:

LUBRICATING FLUID	REGULAR EXPANSION CONE	EXPANSION CONE 5100
	FORCE REQUIRED TO EXPAND TUBULAR MEMBER	
PHPA Mud alone	78,000 lbf	72,000 lbf
PHPA Mud + 7% Lubricant Blend	48,000 lbf	46,000 lbf
100% Lubricant Blend	68,000 lbf	48,000 lbf

- 5 Where: PHPA Mud refers to a drilling mud mixture available from Baroid.

PHPA Mud + 7 % Lubricant Blend refers to a mixture of 93% PHPA Mud and 7% mixture of TorqTrim III, EP Mudlib, and DrillIN-Slid available from Baroid.

10

100% Lubricant Blend refers to a mixture of TorqTrim III, EP Mudlib, and DrillIN-Slid available from Baroid.

15 Thus, in an exemplary embodiment, the use of the expansion cone 5100 reduced the amount of force required to radially expand a tubular member by as much as 30%. This reduction in the required force translates to a corresponding reduction in the overall energy requirements as well as a reduction in the size of required operating equipment such as, for example, hydraulic pumping equipment. During the course of a typical expansion operation, this results in tremendous cost savings to the operator.

20 In a preferred embodiment, the lubricating fluids used with the mandrels 5100, 5200, 5300, 5400, 5500, 5600, 5700, 5800 and 5900 for expanding tubular members have viscosities ranging from about 1 to 10,000 centipoise in order to optimize the injection of the lubricating fluids into the circumferential grooves of the mandrels during the radial expansion process.

In a preferred embodiment, prior to placement in a wellbore, the outer surfaces of the apparatus for expanding tubular members described above with reference to Figs. 1 and 2 are coated with a lubricating fluid to facilitate their placement the wellbore and reduce surge pressures. In a preferred embodiment, the lubricating fluid
5 comprises BARO-LUB GOLD-SEAL™ brand drilling mud lubricant, available from Baroid Drilling Fluids, Inc. In this manner, the insertion of the apparatus into a wellbore, pipeline or other opening is optimized.

Referring to Fig. 17, a preferred embodiment of an expandable tubular 6400 for use in forming and/or repairing a wellbore casing, pipeline, or foundation support will
10 now be described. In a preferred embodiment, the expandable tubular 6400 includes a wall thickness T.

In a preferred embodiment, the wall thickness T is substantially constant throughout the expandable tubular 6400. In a preferred embodiment, the variation in the wall thickness T about the circumference of the tubular member 6400 is less than
15 about 8 % in order to optimally provide an expandable tubular 6400 having a substantially constant hoop yield strength.

In a preferred embodiment, the material composition of and the manufacturing processes used in forming the expandable tubular 6400 are selected to provide a hoop yield strength that varies less than about 10 % about the circumference of the tubular
20 member 6400 in order to optimally provide consistent geometries in the expandable tubular 6400 after radial expansion.

In a preferred embodiment, the expandable tubular 6400 includes structural imperfections such as, for example, voids, foreign material, cracks, of less than about 5 % of the specified wall thickness T in order to optimize the radial expansion of the
25 expandable tubular member 6400. In a preferred embodiment, each expandable tubular 6400 is tested for the presence of such defects using nondestructive testing methods in accordance with industry standard API SR2.

Referring to Fig. 18, a preferred embodiment of an expansion cone 6700 for radially expanding the tubular member 6500 will now be described. The expansion
30 cone 6700 preferably includes a front end 6705, a rear end 6710, and a radial expansion section 6715. In a preferred embodiment, the expansion cone 6700 is used in one or more the embodiments of apparatus and methods for radially expanding a tubular member described above with reference to Figs. 1 - 17. In a preferred embodiment, when the expansion cone 6700 is displaced in the longitudinal direction
35 relative to the tubular member 6500, the interaction of the exterior surface of the radial

expansion section 6715 with the interior surface of the tubular member 6500 causes the tubular member 6500 to expand in the radial direction.

The radial expansion section 6715 preferably includes a first conical outer surface 6720 and a second conical outer surface 6725. The first conical outer surface 6720 includes an angle of attack α_1 and the second conical outer surface 6725 includes an angle of attack α_2 . In a preferred embodiment, the angle of attack α_1 is greater than the angle of attack α_2 . In this manner, the first conical outer surface 6720 optimally radially overexpands the intermediate portion 6530 of the tubular member 6500 and the second conical outer surface 6725 optimally radially overexpands the pre-expanded first and second ends, 6520 and 6535, of the tubular member 6500. In a preferred embodiment, the first conical outer surface 6720 includes an angle of attack α_1 ranging from about 8 to 20 degrees. In a preferred embodiment, the second conical outer surface 6725 includes an angle of attack α_2 ranging from about 4 to 15 degrees. More generally, the expansion cone 6700 may include 3 or more adjacent conical outer surfaces having angles of attack that decrease from the front end 6705 of the expansion cone 6700 to the rear end 6710 of the expansion cone 6700.

Referring to Fig. 19, an alternative preferred embodiment of an expansion cone 6800 for radially expanding the tubular member 6500 will now be described. The expansion cone 6800 preferably includes a front end 6805, a rear end 6810, and a radial expansion section 6815. In a preferred embodiment, the expansion cone 6800 is used in one or more the embodiments of apparatus and methods for radially expanding a tubular member described above with reference to Figs. 1 - 17. In a preferred embodiment, when the expansion cone 6800 is displaced in the longitudinal direction relative to the tubular member 6500, the interaction of the exterior surface of the radial expansion section 6815 with the interior surface of the tubular member 6500 causes the tubular member 6500 to expand in the radial direction.

The radial expansion section 6815 preferably includes an outer surface 6820 having a substantially parabolic outer profile. In this manner, the outer surface 6820 provides an angle of attack that constantly decreases from a maximum at the front end 6805 of the expansion cone 6800 to a minimum at the rear end 6810 of the expansion cone. The parabolic outer profile of the outer surface 6820 may be formed using a plurality of adjacent discrete conical sections and/or using a continuous curved surface. In this manner, the area of the outer surface 6820 adjacent to the front end 6805 of the expansion cone 6800 optimally radially overexpands the intermediate portion 6530 of the tubular member 6500, while the area of the outer surface 6820 adjacent to the rear end 6810 of the expansion cone 6800 optimally radially overexpands the pre-expanded

first and second ends, 6520 and 6535, of the tubular member 6500. In a preferred embodiment, the parabolic profile of the outer surface 6820 is selected to provide an angle of attack that ranges from about 8 to 20 degrees in the vicinity of the front end 6805 of the expansion cone 6800 and an angle of attack in the vicinity of the rear end 6810 of the expansion cone 6800 from about 4 to 15 degrees.

Although illustrative embodiments of the invention have been shown and described, a wide range of modification, changes and substitution is contemplated in the foregoing disclosure. In some instances, some features of the present invention may be employed without a corresponding use of the other features. Accordingly, it is appropriate that the appended claims be construed broadly and in a manner consistent with the scope of the invention.

CLAIMS

1. An expansion cone for radially expanding a tubular member, comprising:
a paraboloid expansion cone body.
- 5 2. The expansion cone of claim 1, wherein the angle of attack of the outer surface of the paraboloid expansion cone body increases in a continuous manner from one end of the paraboloid expansion cone body to the opposite end of the paraboloid expansion cone body.
- 10 3. The expansion cone of claim 1 or 2 wherein:
at least a portion of the paraboloid expansion cone body has an angle of attack of 25°.
- 15 4. The expansion cone of any one of claims 1, 2 or 3 further comprising:
a lubricant on an outer surface of the paraboloid expansion cone body.
5. The expansion cone of any one of claims 1 to 4 further comprising:
one or more grooves formed in an outer surface of the paraboloid expansion
20 cone body.
6. The expansion cone of any one of claims 1 to 5 further comprising:
one or more axial flow passages defined within the paraboloid expansion cone
body.
- 25 7. The expansion cone of claim 5, wherein the grooves comprise circumferential grooves.
8. The expansion cone of claim 5, wherein the grooves comprise spiral grooves.
- 30 9. The expansion cone of any one of claims 5, 7, or 8, wherein the grooves are concentrated around an axial midpoint of the paraboloid expansion cone body.
10. The expansion cone of claim 6, wherein the axial flow passages comprise axial
35 grooves.

11. The expansion cone of claim 10, wherein the axial grooves are spaced apart by at least about 3 inches in the circumferential direction.
12. The expansion cone of claim 5, further comprising flow passages, wherein the
5 flow passages are positioned within the paraboloid expansion cone body.
13. The expansion cone of claim 12, wherein the flow passages are coupled to one or more grooves.
- 10 14. The expansion cone of claim 12 or 13, wherein one or more of the flow passages include inserts having restricted flow passages.
15. The expansion cone of claim 12 to 14, wherein one or more of the flow passages include filters.
- 15 16. The expansion cone of any one of claims 5, 7 to 9, or 12 to 15, wherein the cross-sectional area of the grooves ranges from $1.29 \times 10^{-7} \text{ m}^2$ to $3.226 \times 10^{-5} \text{ m}^2$ ($2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$).
- 20 17. The expansion cone of any one of claims 6, 10, or 11, wherein the cross-sectional area of the axial flow passages ranges from about $1.29 \times 10^{-7} \text{ m}^2$ to $3.226 \times 10^{-5} \text{ m}^2$ ($2 \times 10^{-4} \text{ in}^2$ to $5 \times 10^{-2} \text{ in}^2$).
- 25 18. The expansion cone of any one of claims 5, 7 to 9, or 12 to 16, wherein the grooves include:
a flow channel having a first radius of curvature;
a first shoulder positioned on one side of the flow channel having a second radius of curvature; and
a second shoulder positioned on the other side of the flow channel having a
30 third radius of curvature.
19. The expansion cone of claim 18, wherein the first, second and third radii of curvature are substantially equal.
- 35 20. The expansion cone of any one of claims 6, 10, 11, or 17, wherein the axial flow passages include:

a flow channel having a first radius of curvature;
a first shoulder positioned on one side of the flow channel having a second
radius of curvature; and
a second shoulder positioned on the other side of the flow channel having a
5 third radius of curvature.

21. The expansion cone of claim 20, wherein the first, second and third radii of
curvature are substantially equal.

10 22. The expansion cone of claim 20, wherein the second radius of curvature is
greater than the third radius of curvature.

15

20

25

30

35